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# CONTRIBUTION OF MACROPOROSITY TO INFILTRATION INTO A CONTINUOUS CORN NO-TILLED WATERSHED: IMPLICATIONS FOR CONTAMINANT MOVEMENT

W.M. EDWARDS[1], M.J. SHIPITALO[1] and L.D. NORTON[2]

[1] *USDA-ARS, North Appalachian Experimental Watershed, Coshocton, OH 43812, U.S.A.*
[2] *USDA-ARS, National Soil Erosion Research Laboratory, West Lafayette, IN 47907, U.S.A.*

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ABSTRACT

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Rainfall and runoff were measured for many years on small watersheds on 10–15% slopes in east-central Ohio. Surface runoff from watersheds used for corn (*Zea mays* L.) production was high with conventional tillage and very low with no-tillage. A 50-year storm produced 15 times more runoff from a plowed watershed than from a mulch-covered no-till watershed. Reduced runoff from the no-till surface resulted in increased percolation and enhanced the potential for transport of agricultural chemicals to the groundwater. The mulched surface of the no-till watershed also created a favorable environment for the deep burrowing earthworm, *Lumbricus terrestris* L., whose burrows can transmit water rapidly downward through the soil profile, thus contributing to the high infiltration rates.

Open biopores and smaller structural pores were counted and measured to characterize the major flow paths of water movement in the no-till soil. Photos of horizontal surfaces at 2.5-, 7.5-, 15-, and 30 – cm depths and vertical faces of impregnated samples from the 1- and 5-cm depths were evaluated by image analysis. Number of pores was inversely proportional to pore diameter, however pores in the 0.05-1.0-mm diameter range accounted for less porosity than did those in the 1.0-5.0-mm range. The large pores were nearly vertical earthworm burrows and were continuously open from near the surface to the bedrock. Surface applications of lime increased subsoil pH in the no-till watershed but had little effect below the plow sole in the tilled watershed, suggesting that rapid movement of water in large pores can enhance chemical migration into the subsoil.

## INTRODUCTION

At the USDA-ARS North Appalachian Experimental Watershed (NAEW) near Coshocton, Ohio, small, gaged watersheds have been used for 50 years to evaluate the effects of management on infiltration, runoff and erosion from sloping residual soils of the unglaciated uplands of the Allegheny Plateau. Early investigations indicated that intense, summer thunderstorms produced surface crusts on conventionally tilled topsoils (spring plowed, disked, and

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harrowed), reducing infiltration and thereby increasing runoff and erosion. Similar storms on the same watersheds produced little runoff in years when meadow or small grain crops protected the soil surface from crusting.

As an attempt to increase row crop production without concomitant increases in runoff and erosion, the "no-till" management practice for corn production was developed, tested, and refined. With no-tillage, seeds are planted in a narrow slit opened in growing sod, cover crop, or in dead residue from the preceding crop. Competition by weeds for nutrients, water, and energy during the growing season is controlled by applications of herbicides rather than by mechanical cultivation. The growing crop emerges through dead or dying residue which protects the surface from crusting, much as if it were covered by a growing meadow or small grain crop.

No-till corn (*Zea mays* L.) yields under our soil and climatic conditions are comparable to those for corn grown with conventional tillage while runoff and erosion are greatly reduced. However, after several years of continuous no-tillage corn production, changes in the soil are apparent. Without topsoil mixing by tillage, the distributions of pH, organic matter, and fertility with depth are changed. Bulk density in the topsoil is increased as is macroporosity (Edwards, 1982). The mulch cover keeps the surface cooler and wetter, which retards early season crop growth but favors grain filling and dry matter production during the hot, dry summer months.

The mulch cover on a no-tillage field also affects biological activity in the soil (Doran, 1980). In particular, it creates a favorable environment for *Lumbricus terrestris* L. These large earthworms feed on organic matter on the soil surface and make nearly vertical burrows to depths of 2 m or more in some soils (Ehlers, 1975). The burrows are commonly 3–10 mm in diameter and act as continuous channels through which water can rapidly flow.

For years, these worms and their burrows have been noted and documented in pastures, meadows, and other vegetated fields (Lee, 1985). Recently, the effects of tillage or lack of tillage on worm populations in cropland have been documented (De St. Remy and Daynard, 1982). Mackay and Kladivko (1985) reported that the number of earthworms found in no-tilled soybean (*Glycine max* L.) fields was more than double that in plowed fields, whereas the tillage treatment had no effect in corn fields. In Brazil, no-tillage for 4 years increased earthworm populations 9-fold as compared to conventional tillage (Derpsch et al., 1986).

Germann et al. (1984) showed that water and soluble chemical tracers (including dye) moved rapidly through the soil profile in large worm holes during simulated rainstorms. However, other macropores or preferential flow channels are also involved in the movement of water and chemicals in soil. Dekker and Bouma (1984) reported that cracks in a Dutch clay soil resulted in short-circuiting of water carrying nitrogen, whereas Rasmuson and Neretnieks (1986) used radionuclides to show preferential flow continuing in cracks in rock structures below soils. Smith et al. (1985) and Germann et al. (1987) measured and modeled the movement of bacteria through soil macropores in undisturbed soil columns. Several examples of the effects of conservation tillage on soil properties and processes that affect the movement of agricultural chemicals through the soil are reported by Logan et al. (1987).

Runoff records for NAEW watersheds that have been used for no-till corn production for many years indicate that infiltration rates are greater in soils under no-till management than when they were conventionally tilled. However, questions about the movement of water and chemicals through the non-tilled soil profile remain. The objective of this study was to characterize the porosity and several indicator parameters in the soil profile of a watershed that has been farmed for more than 20 years under continuous no-tillage corn, with emphasis on the vertical orientation of biopores that appear to be involved in the downward movement of water and potential contaminants.

## METHODS

### *Site characteristics*

Field work was done in or near watershed 191 at the NAEW. Rainfall amounts and intensities at this 0.5-ha watershed have been measured since 1939 using a standard recording US Weather Bureau raingage. Runoff was measured with a 2-foot (60 cm) H flume. Prior to 1964 conventional tillage was used in the production of corn, small grains, and grass-legume meadow in rotation. Since 1964, the crop has been continuous no-till corn, with all crop residue being left on the surface. In most years, cattle manure has been applied in late winter.

Fertility has been maintained with broadcast applications of N-P-K at planting time, with corn yields normally ranging from 9 to 11 Mg ha$^{-1}$. Weed control has been by herbicides (mainly triazines) applied at rates of 3–5 kg ha$^{-1}$. In recent years, various insecticides have been used at normal rates in the row at planting time.

Average slope in the watershed is 9% with the lower part a little steeper than the upper. The dominant soil is Westmoreland silt loam, (fine-loamy, mixed, mesic, Ultic Hapludalf) which is developed in colluvium and residuum from weathered sandstone and siltstone bedrock that lies approximately 1 m below the surface. The uppermost 5–8 cm of the A horizon is very dark grayish brown (10YR 3/2) silt loam. The dark color is due to an accumulation of organic matter near the surface, since residue and additions of manure have not been incorporated during the 20 years of no-tillage (Dick, 1983). This darkened zone has weak, medium platy structure, parting to moderate, medium granular. The remainder of the old plow layer (Ap horizon) to a depth of about 21 cm is brown (10YR 4/3) friable silt loam, with moderate, medium, subangular blocky structure. The subsoil (Bt horizon) is mostly yellowish brown (10YR 5/6) silt loam in the upper part, and loam or channery loam in the lower part. Small chips of siltstone and fine-grained sandstone, mostly $< 5$ cm in diameter and

< 1 cm thick, comprise 5–10% of the A and Bt horizons and 15–25% of the BC horizon.

Under conventional tillage, this soil has moderate permeability (1.5–5 cm $h^{-1}$), a moderate to deep rooting zone (> 1 m), and a moderate available moisture capacity (15–23 cm). Additional physical and chemical characteristics are given by Kelly et al. (1975).

*Field and laboratory procedures*

Porosity in the horizontal plane was determined at four depths (2.5-, 7.5-, 15-, and 30-cm) at eight sites in the watersheds. Flat, smooth surfaces were prepared at each depth and photographed using oblique illuminations. Only pores wider than approximately 0.4 mm and continuous with depth were distinguished from the soil matrix using this technique. Pores with these characteristics are generally attributed to animal or root activity, hence are termed biopores. Details of the surface preparation and photographic techniques are given elsewhere (Edwards et al., 1988).

Pores in the vertical plane were characterized using undisturbed samples taken near the same eight sites. The samples were slowly air-dried and impregnated with Scotchcast #3 epoxy resin* following the procedure of Innes and Pluth (1970). Vertically oriented blocks (5 cm wide × 7.5 cm high) of the impregnated soil were cut on a diamond saw and one face was polished with 600 mesh grit.

Image analysis was performed on the photos taken in the field and directly on the polished blocks at 10X magnification using a Leitz TAS Plus image analyzer* (Serra, 1982). Reflected light illumination in concert with a Leitz Ortholux microscope* and image inversion was used to discriminate pores in the polished blocks from the light colored soil matrix. Pores < 0.4 mm equivalent circular diameter (ecd) on the field photos and those < 0.05 mm ecd on the impregnated samples were removed from the analysis by erosion. Each pore was analyzed for area, perimeter, ecd, and feret maximum and minimum diameters at 5-degree intervals (Norton, 1987). In the vertically oriented samples, pore shape was quantified using the $A/P^2$ measurement and classification according to Jongerius and Bisdom (1981) into planar ($A/P^2$ < 0.015), elongate ($A/P^2$ 0.015–0.04) or rounded ($A/P^2$ > 0.04) classes.

Porosity in each of the eight vertically oriented polished blocks was determined by evaluating a 1.44 $cm^2$ area at three locations in the 0–1.2 cm depth interval and at three locations within the 4.4–5.6-cm interval. For the horizontally oriented photos, a 30.5 by 30.5 $cm^2$ area in the middle of each photo was analyzed.

Soil reaction was measured with a pH meter in 1:1 soil:water slurries of samples taken adjacent to the eight pore-analysis sites in watershed 191 and at

* Mention of a particular product or company does not imply endorsement or preference over similar products not mentioned.

eight random sites in a nearby conventionally tilled field and in a pine forest of the same soil type. Organic carbon content was determined on air-dried samples using the Walkley and Black (1934) method.

## RESULTS AND DISCUSSION

### *Hydrology*

During 1979–1982, runoff from the long-term no-till watershed 191 (8.8 mm) was one-eightieth of that from a nearby conventionally tilled corn watershed number 123 (708.0 mm). Thus, under the storm conditions experienced during that 4-year period, no-till management had a consistent runoff-reducing effect. In addition, the hydrologic performance of the no-till watershed under severe storm conditions is of interest. Cumulative rainfall and runoff from both watersheds for the largest storm of the study period, a 50-year return period, 24-hour storm (USDC, 1961), is shown in Fig. 1. Total rainfall in the 17-hour period was 116 mm, 33 mm of which fell at intensities $> 25.4\,\mathrm{mm\,h^{-1}}$. Runoff from the conventionally tilled watershed amounted to 46.2 mm, or 40% of rainfall, while 3.1 mm ($< 3\%$ of rainfall) ran off the no-till surface.

Infiltration is by definition a surface phenomenon. During large storms,

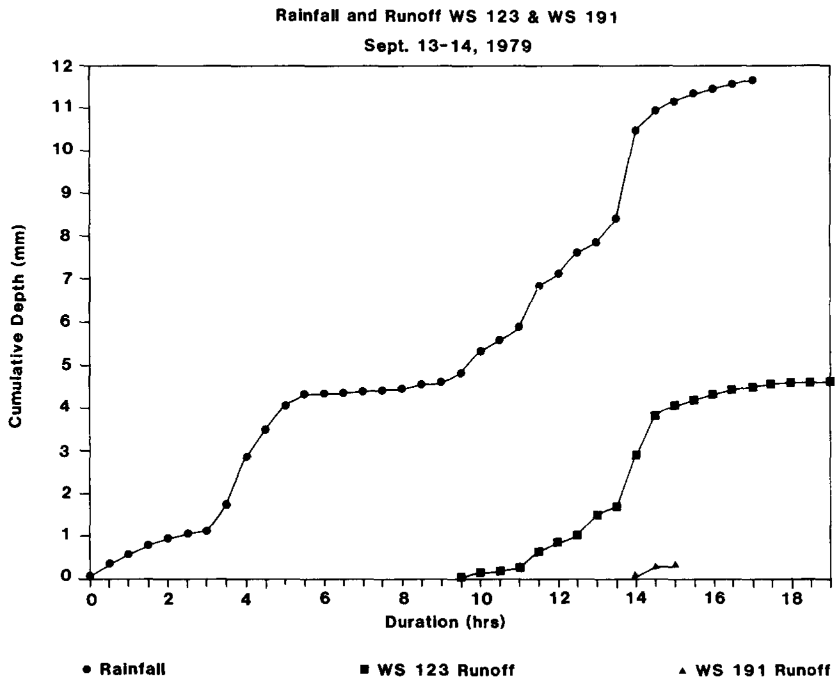


Fig. 1. Cumulative rainfall and runoff during a 50-year storm which occurred Sept. 13–14, 1979 for conventionally tilled (WS 123) and no-till (WS 191) corn watersheds.

however, subsurface flow characteristics become increasingly important. Unless infiltrating water is conducted away from the surface at a rate equal to the rainfall rate, ponding or runoff will occur. After 20 years of continuous no-tillage, 20 years without loosening the plow layer, compaction from planting and harvesting traffic has increased bulk density and reduced near-surface porosity (Edwards, 1982), which according to conventional theory should lead to decreased vertical conductivity. But as shown in Fig. 1, runoff from even a 50-year storm was minimal, indicating that the remaining porosity allows for rapid infiltration and water transmission.

*Biopores*

Figure 2 shows a representative photo of the horizontal surfaces that were evaluated by image analysis to characterize the near-surface soil through which rapid infiltration takes place. This picture, taken at the 15-cm depth, shows several nearly round earthworm burrows, through which rapid infiltration has been shown to occur (Germann et al., 1984). The largest of these worm holes (> 4 mm diameter) are burrows of *Lumbricus terrestris*. Many of the vertical 2- to 4- mm diameter holes at this and lower depths appear to have been made by juvenile *L. terrestris*.

Nearer the surface, many of the biopores in this size range appeared to have been made by shallow burrowing earthworm species or other soil fauna that forage for food within the near-surface horizons. These channels were predomi-

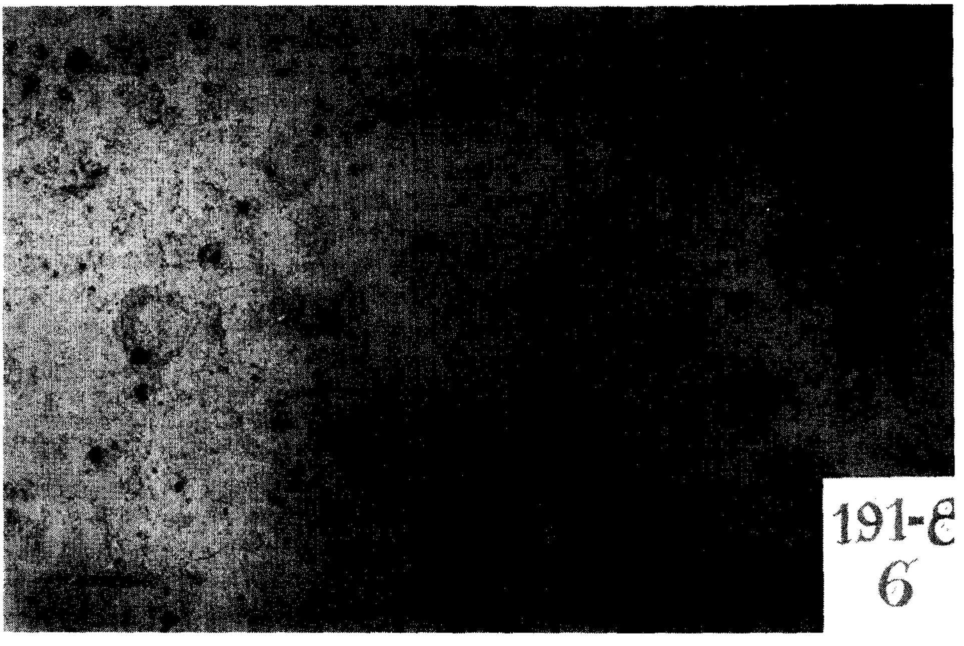


Fig. 2. Photo of a 30- by 45-cm horizontal plane at 15-cm depth in watershed 191.

nantly horizontal, but had some vertical components and some openings to the soil surface. They were often partially filled with casts, but in most instances appeared to be preferential flow paths within the soil matrix. Linden and others have suggested that interconnection of these small shallow, topsoil channels with the large, nearly vertical, deep penetrating *L. terrestris* burrows may be an important condition that promotes rapid infiltration in soils farmed with reduced tillage practices (D. Linden, USDA-ARS, St. Paul, MN, pers. commun., 1987).

The total number of $> 0.4$ mm ecd pores and their size distribution as a function of depth as determined by image analysis of photos taken at the 4 depths and 8 sites are presented in Table 1. Over the entire range of pore classes, there is a trend for more pores as a function of depth. In five of the six arbitrary size classes selected, there were more pores at the lowest depth than at any other. Although the uppermost two depths had consistently fewer pores than the lower two depths, these differences were not significant at $P = 0.90$ due to high site-to-site variability.

Over 75% of the pores observed were $< 1.0$ mm ecd. Since earthworm burrows are generally 1–10-mm in diameter (Lee, 1985), most of the pores detected by the image analyzer are not attributable to worm activity. Tippkoetter (1983) compared diameters, branching, and tapering of 0.1–1.0-mm diameter pores in subsoils with the morphological characteristics of plant roots sampled at similar depths and concluded that most pores in that size range were made by plant roots.

Most of the $> 5$-mm ecd pores examined were made by *L. terrestris*. The average ecd of 600 *L. terrestris* burrows $> 5.0$ mm in diameter as measured at the 5–10-cm depth in watershed 191 was 7.66 mm (Fig. 3). Burrows $> 10$ mm ecd were not uncommon. Juvenile *L. terrestris* were frequently found in 2–4-mm diameter burrows.

*Structural pores*

Although it is difficult to distinguish biopores from structural pores based on ecd alone, at the extremes of the size distribution, there can be little doubt. We

TABLE 1

Pore size distribution (equivalent circular diameter) as a function of depth in watershed 191

| Depth | Pore size classes (mm) | | | | | |
|---|---|---|---|---|---|---|
| (mm) | 0–1 | 1–2 | 2–3 | 3–4 | 4–5 | > 5 |
| | | | (No. pores $m^{-2}$) | | | |
| 25 | 7,682 | 2,045 | 753 | 323 | 188 | 145 |
| 75 | 9,385 | 1,979 | 759 | 344 | 230 | 139 |
| 150 | 11,517 | 2,381 | 861 | 417 | 229 | 151 |
| 300 | 14,396 | 2,745 | 901 | 363 | 256 | 205 |

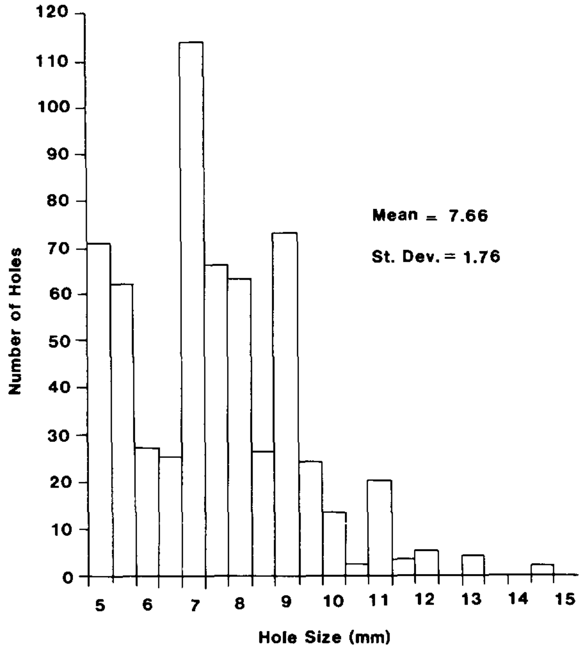


Fig. 3. Size distribution of 600 > 5 mm diameter burrows of *Lumbricus terrestris* in watershed 191.

found worms occupying only smooth-walled, sometimes mucus-lined cylindrical channels, usually > 1 mm in diameter. Roots can make finer holes (Tippkoetter, 1983) and they appear to grow well in worm holes of any size.

Examination of pore size distributions down to < 0.05 mm ecd using the polished blocks provided a basis for separating earthworm burrows and other biopores (> 1 mm ecd) from the finer distribution which contains structural pores (Fig. 4). The distribution of structural pores in this long-term no-till field was quite different from that of the biopores (Fig. 5). There was little difference in amount or distribution of the smaller pores in near-surface depths; and unlike those of the biopore size range, they contribute little to total porosity (Fig. 5).

When viewed in a vertical plane, few of the pores in the 0.05–5.0-mm diameter size range are round. Elongate and planar shapes, especially in the larger size ranges dominated (Fig. 5). These pore shapes support the biopore data (round holes in the horizontal plane but continuous with depth) and the supposition that the large, vertical biopores could be very important pathways for rapid infiltration.

*Chemical implications*

With a lack of tillage to incorporate residues, decaying organic matter accumulates near the surface (Fig. 6). The decomposition of this material and

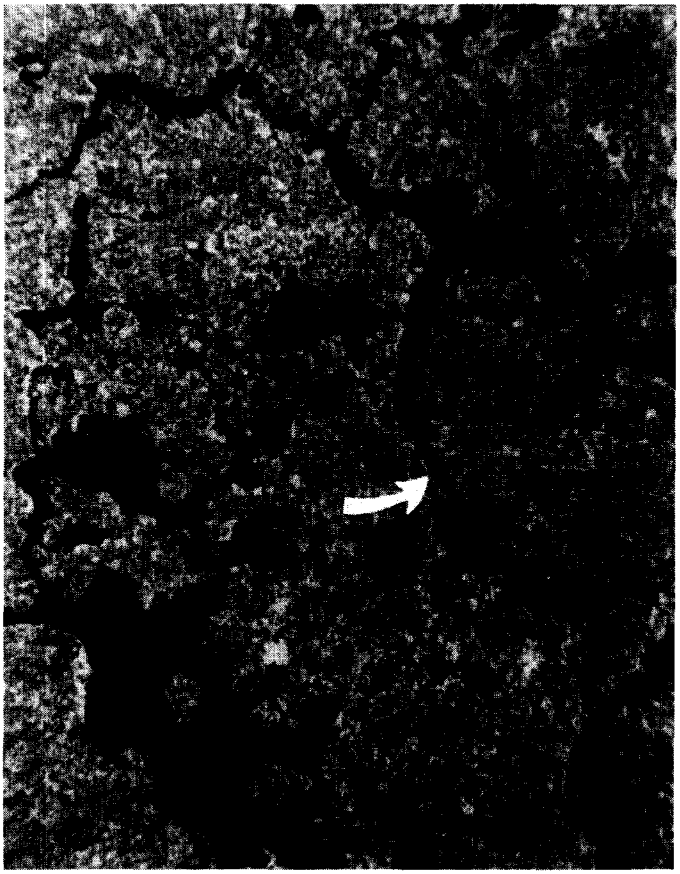

Fig. 4. Photomicrograph of "structural" pores (designated by arrow) in vertically oriented polished block. Frame width = 1.15 mm.

the accompanying increase in cation exchange capacity in the uppermost few cm of soil could serve as a potential sink for nutrients and pesticides. However, comparison of the pH distribution in the no-till corn field to that in a nearby conventionally tilled corn field and an uncultivated pine forest (Fig. 7) suggests that the effect of periodic lime applications to the non-tilled surface has extended well below the original depth of plowing. This indicates that under some conditions, water carrying the acid-counteracting components of the surface applied limestone bypasses much of the increased exchange capacity of the upper soil matrix. Bouma et al. (1981) define this process as "short-circuiting" and present a method for measuring it in the field. The amount of lime spread on the no-tillage and nearby conventionally tilled field (Fig. 7) has been comparable during the last 20 years. With periodic tillage, the effect of the lime treatments appears to be confined to the plow layer. The pine forest was an abandoned crop field in 1935 which was reforested to several pine species in

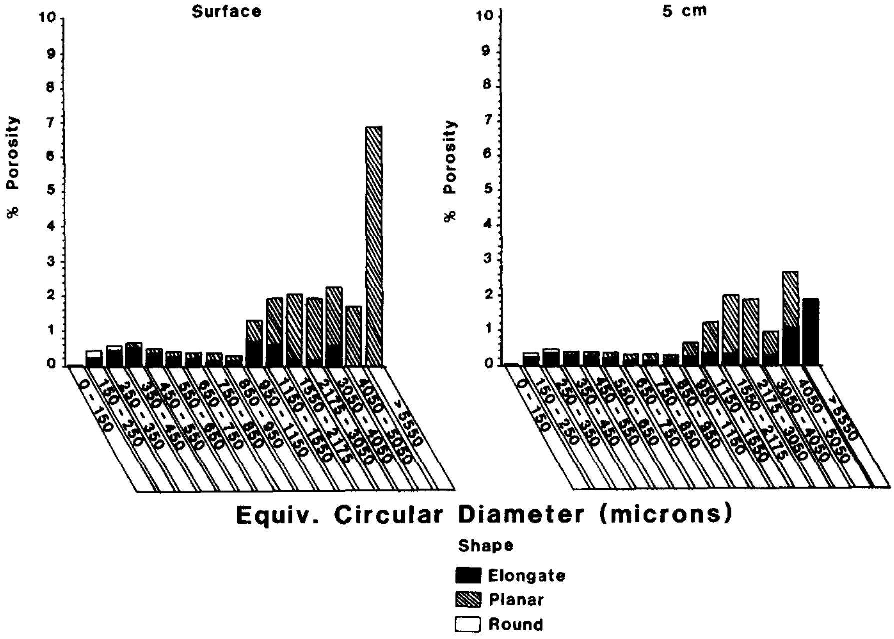


Fig. 5. Average pore sizes and shape distributions as measured in the vertical plane at 0–1-cm and 4.5–5.6-cm depths in watershed 191.

1939 without any known lime application. All three sites have the same soil series and are within 200 m of one-another.

Several observations support the premise that large vertically continuous biopores are important pathways of infiltrating water in this long-term no-till corn watershed. They include: the apparent deep movement of the divalent Ca ion (as indicated by pH) in spite of the increased organic matter content near the surface of the no-till field; the relative paucity of structural pore space (mesopores, as defined by Luxmoore, 1981) with respect to biopores; the vertical orientation and continuity of the larger biopores; and the dye-stained *Lumbricus terrestris* burrows following surface sprinkling with colored water (Germann et al., 1984).

## CONCLUSIONS

The no-till management practice was designed to reduce surface runoff and erosion that accompanied corn production when this and similar soils were farmed with conventional tillage. The practice reduced surface runoff, as has been shown; but the lack of tillage and the associated mulch-covered surface have favored the development and preservation of a system of vertically

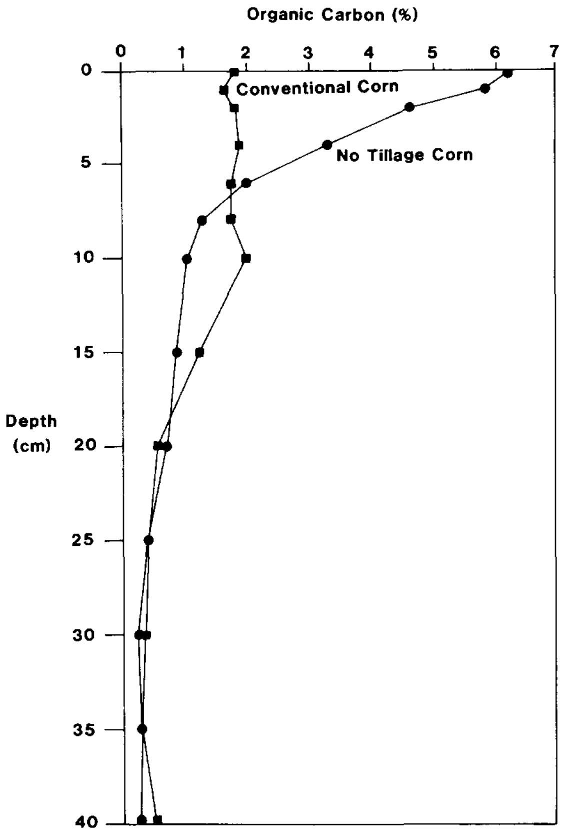


Fig. 6. Organic carbon distribution with depth in no-till and conventionally tilled corn fields.

continuous macropores, through which infiltrating water can rapidly flow, by-passing much of the increased exchange capacity of the soil matrix. The deep effects of surface applied lime treatments on the long-term no-till surface indicate that water and chemical movement in the non-tilled soil are controlled by mechanisms that differ from those that are dominant under conventional tillage. Other effects of by-passing or short-circuiting flow upon subsurface water quality will certainly vary widely in both time and space.

ACKNOWLEDGEMENT

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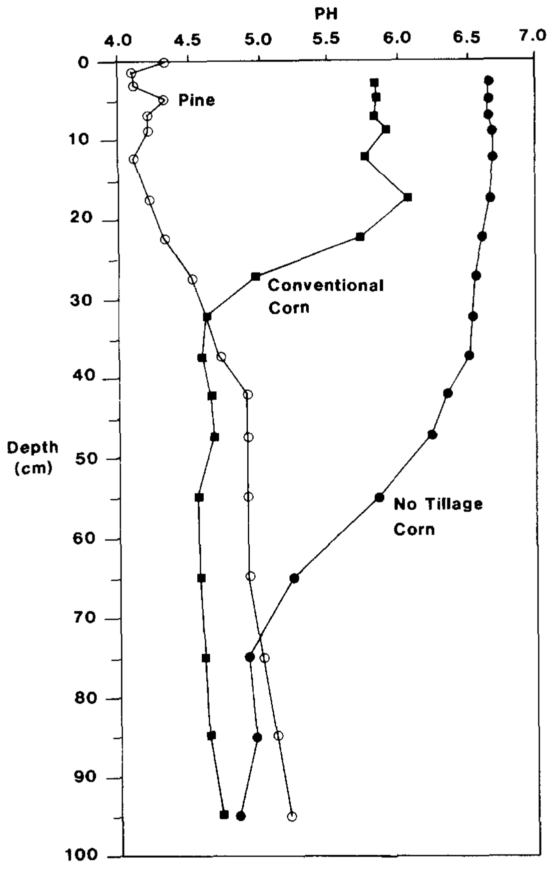


Fig. 7. Depth distribution of pH as influenced by management. Each distribution represents the average of eight replications.

## REFERENCES


Bouma, J., Dekker, L.W. and Muilwijk, C.J., 1981. A field method for measuring short-circuiting in clay soils. J. Hydrol., 52: 347–354.

De St. Remy, E.A. and Daynard, T.B., 1982. Effects of tillage methods on earthworm populations in monoculture corn. Can. J. Soil Sci., 62: 699–703.

Dekker, L.W. and Bouma, J., 1984. Nitrogen leaching during sprinkler irrigation of a Dutch clay soil. Agric. Water Manage., 9: 37–45.

Derpsch, R., Sidiras, N., and Roth, C.R., 1986. Results of studies made from 1977 to 1984 to control erosion by cover crops and no-tillage techniques in Parana, Brazil. Soil Tillage Res., 8: 253–263.

Dick, W.A., 1983. Organic carbon, nitrogen, and phosphorus concentrations and pH in soil profiles as affected by tillage intensity. Soil Sci. Soc. Am. J., 47: 102–107.

Doran, J.W., 1980. Soil microbial and biochemical changes associated with reduced tillage. Soil Sci. Soc. Am. J., 44: 765–771.

Edwards, W.M., 1982. Predicting tillage effects on infiltration. In: Predicting Tillage Effects on Soil Physical Properties and Processes. Am. Soc. Agron. Spec. Publ., 44: 105–115.

Edwards, W.M., Norton, L.D. and Redmond, C.E., 1988. Characterizing macropores that affect infiltration into non-tilled soil. Soil Sci. Soc. Am. J., 52 (2): 483–487.

Ehlers, W., 1975. Observations on earthworm channels and infiltration on tilled and untilled loess soil. Soil Sci., 119: 242–249.

Germann, P.F., Edwards, W.M. and Owens, L.B., 1984. Profiles of bromide and increased soil moisture after infiltration into soils with macropores. Soil Sci. Soc. Am. J., 48: 237–244.

Germann, P.F., Smith, M.S. and Thomas, G.W., 1987. Kinematic wave approximation to the transport of *Escherichia coli* in the vadose zone. Water Resour. Res., 23: 1281–1287.

Innes, R.P. and Pluth, D.J., 1970. Thin section preparation using an epoxy impregnation for petrographic and electron microprobe analysis. Soil Sci. Soc. Am. Proc., 34: 483–485.

Jongerius, A. and Bisdom, E.B.A., 1981. Porosity measurements using the Quantimet 720 on backscattered electron scanning images of thin sections of soils. In: E.B.A. Bisdom (Editor), Submicroscopy of Soils and Weathered Rocks. Centre for Agric. Publ. and Doc., Wageningen, pp. 207–216.

Kelley, G.E., Edwards, W.M., Harrold, L.L. and McGuinness, J.L., 1975. Soils of the North Appalachian Experimental Watershed. USDA Misc. Publ. No. 1296b, 145 pp.

Lee, K.E., 1985. Earthworms — Their ecology and Relationships with Soils and Land Use. Academic Press. New York, NY, 411 pp.

Logan, T.J., Davidson, J.M., Baker, J.L. and Overcash, M.R., 1987. Effects of conservation tillage on groundwater quality: Nitrates and pesticides. Lewis Publishers, Chelsea, MI, 292 pp.

Luxmoore, R.J. 1981. Micro-, meso-, and macroporosity of soil. Soil Sci. Soc. Am. J., 45: 671–672.

Mackay, A.D. and Kladivko, E.J., 1985. Earthworms and rate of breakdown of soybean and maize residues in soils. Soil Biol. and Biochem., 17: 851–857.

Norton, L.D., 1987. Micromorphological study of surface seals developed under simulated rainfall. Geoderma, 40: 127–140.

Rasmuson, A. and Neretnieks, I., 1986. Radionuclide transport in fast channels in crystalline rock. Water Resour. Res., 22: 1247–1256.

Serra, J., 1982. Image Analysis and Mathematical Morphology. Academic Press, London, 610 pp.

Smith, M.S., Thomas, G.W., White, R.E. and Ritonga, D., 1985. Transport of *Escherichia coli* through intact and disturbed soil columns. J. Environ. Qual., 14: 87–91.

Tippkoetter, R., 1983. Morphology, spatial arrangement and origin of macropores in some Hapludalfs, West Germany. Geoderma, 29: 355–371.

U.S. Dept. Commerce, 1961. Rainfall frequency atlas of the United States for durations from 30 minutes to 24 hours and return periods from 1 to 100 years. Washington D.C., 115 pp.

Walkley, A. and Black, I.A., 1934. An examination of the Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. Soil Sci., 37: 29–38.